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EDITED BY
Emmanuel Arthur,
Aarhus University, Denmark

REVIEWED BY
Peter N. Eze,
Botswana International University of Science and Technology, Botswana
YingWu Shi,
Institute of Microbiology, China

*CORRESPONDENCE
Leticia Jiménez
lsjimenez@utpl.edu.ec

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# Long-term grazing exclusion enhances soil carbon and nitrogen stocks in tropical dry forests of southern Ecuador

Leticia Jiménez[1*], Pablo Ramón[1,2], Jhonattan Sarango[3], Juan Ignacio Burneo[1], Johana Gusmán[3] and Elizabeth Gusmán-Montalván[1,2]

[1]Departamento de Ciencias Biológicas y Agropecuarias, Universidad Técnica Particular de Loja, Loja, Ecuador, [2]Laboratorio de Ecología Tropical y Servicios Ecosistémicos, Universidad Técnica Particular de Loja, Loja, Ecuador, [3]Alumni-Carrera de Ingeniería Agropecuaria, Universidad Técnica Particular de Loja, Loja, Ecuador

Anthropogenic activities, particularly agriculture and cattle ranching, transform forest ecosystems and alter soil properties in tropical dry forests. This study quantified changes in carbon (C) and nitrogen (N) stocks and soil nutrient composition across three land use types: excluded forest (EF - protected from grazing for 8 years), non-excluded pasture (NEP), and maize cropland (Cr) in southern Ecuador. We established three 1-ha plots per land use type and collected 225 soil samples (0–10 cm depth) for physicochemical analysis using standard methods including loss-on-ignition for C determination and Kjeldahl method for N analysis. Carbon stocks were significantly higher in excluded forest (18.09 Mg/ha) compared to cropland (17.67 Mg/ha, $p<0.05$), while nitrogen stocks were elevated in cropland (2.66 Mg/ha) versus excluded forest and pasture (2.04 Mg/ha). Soil texture, electrical conductivity, phosphorus, and potassium concentrations differed significantly among land use types ($p<0.05$). Excluded forests showed the highest calcium and magnesium concentrations, while croplands exhibited elevated phosphorus and potassium levels due to fertilization practices. These findings demonstrate that grazing exclusion enhances soil carbon sequestration in tropical dry forests and highlight the importance of forest conservation strategies for climate change mitigation.

KEYWORDS
**soil fertility, nutrients, soil forest, soil carbon, grazing**

## 1 Introduction

Deforestation, fragmentation, and overgrazing represent the main drivers of global change, affecting ecosystem functioning and biodiversity conservation (1). In drylands, grazing constitutes the predominant land use (2), with global livestock grazing pressures projected to increase by up to 70% by 2050 (3). This intensification poses significant

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challenges for ecosystem management and conservation, particularly in vulnerable dry forest ecosystems. This intensification poses significant challenges for ecosystem management and conservation, particularly in vulnerable dry forest ecosystems.

Intensive grazing significantly modifies ecosystem structure, composition, and functions in dry forests, with cascading effects on multiple components. At the vegetation level, grazing modifies plant cover, biomass, and species richness (4), while simultaneously altering multiple physical and chemical soil properties including bulk density, moisture, pH, and nutrient content (5). Recent studies have demonstrated that these modifications also disrupt microbial communities and soil enzyme activities crucial for nutrient cycling and carbon stabilization processes (6). Overgrazing creates particularly problematic nutrient imbalances through heterogeneous redistribution patterns. Animals consume vegetation containing essential nutrients and subsequently concentrate their droppings in specific areas, resulting in enriched zones and depleted ones (5). While moderate grazing can stimulate nitrogen mineralization through nitrogen-rich waste products (7), high-intensity and long-term grazing slows down nitrogen cycles by reducing nitrogen-rich species and increasing nitrogen-poor species (8).

The physical impacts of overgrazing extend to fundamental soil properties and ecosystem services. Overgrazing deteriorates topsoil structure, alters pore distribution, increases bulk density, and decreases soil aggregate stability and infiltration rate (9). Advanced imaging techniques have revealed that these modifications lead to significant alterations in soil pore networks and hydraulic conductivity, with cascading effects on water retention and plant-available water (10). These changes compromise soil carbon sequestration potential and ecosystem resilience to climate change (11). Establishing fenced areas to exclude domestic livestock grazing has emerged as an effective strategy to counteract forest degradation (12, 13). This approach promotes plant productivity, species richness, and soil fertility (14, 15). Recent long-term studies demonstrate that grazing exclusion can significantly enhance soil carbon sequestration, with accumulation rates between 0.35 and 0.72 Mg C $ha^{-1}$ $yr^{-1}$ depending on climatic conditions and initial degradation status (16, 17).

Despite growing evidence of grazing exclusion benefits, significant knowledge gaps remain regarding the comparative effects of different land management practices on soil properties and carbon dynamics in Neotropical dry forests. Most previous studies have focused on temperate or subtropical systems, with limited research quantifying soil physical and chemical responses to grazing exclusion in the specific climatic and edaphic conditions of South American dry forests. Furthermore, few studies have simultaneously compared excluded forests, grazed pastures, and croplands within the same landscape context, making it difficult to establish clear management recommendations for ecosystem restoration. The spatial heterogeneity of grazing effects, strongly modulated by topography, soil texture, and precipitation patterns (18), requires landscape-specific assessments to develop effective management strategies for dry forest conservation and restoration.

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The spatial heterogeneity of grazing effects, strongly modulated by topography, soil texture, and precipitation patterns (18), require landscape-specific assessments to develop effective management strategies for dry forest conservation and restoration. Our study addresses these knowledge gaps by analyzing the effects of grazing exclusion on soil properties and ecosystem services in dry forests of southern Ecuador.

Specifically, we aimed to (1): quantify and compare soil physical and chemical properties (texture, bulk density, pH, electrical conductivity, and nutrient content) across three distinct land management types: excluded forest, non-excluded pastures, and croplands (2); determine how soil carbon and nitrogen stocks vary among these land use types; and (3) evaluate the soil's carbon sequestration potential under different management regimes. This comparative approach provides essential information for understanding soil capacity to store carbon and nitrogen under different management practices, contributing to evidence-based restoration strategies and climate change mitigation efforts in Neotropical dry forests.

# 2 Materials and methods

## 2.1 Study site

This study was conducted in the Zapotillo county (cantón Zapotillo in Spanish), located in Loja province, in the southern of Ecuador. Specifically, we set our experimental plots in the Palo Santo valley (4o 19′ S, 80o 17′ W) which gets its name from the vernacular denomination of this tree species (15). The mean annual temperatures vary between 18°C and 26°C; and annual precipitation ranges from 660 to 1300 mm. Climate presents two distinct seasons, a dry one that goes from May to November and a rainy period from December to April (19). Many of the forest species of this dry forest suffer great anthropogenic pressure, for instance tree species such as *Handroanthus chrysanthus*, *Terminalia valverdeae* and *Loxopterygium huasango* are cut down for their valuable wood (20) whereas browsing of goats mainly affects species such as *Bursera graveolens*, *Eriotheca ruiz*, *Cochospermun vitifolium*, among others (21).

Within the Palo Santo valley, a representative fraction (35 ha) of dry forest was fenced off in 2010 by the (22). The fence, which excludes the presence of cattle, goats and white- tailed deer (*Odocoileus virginianus*), is made of 9 lines of barbed wire, with a distance between posts of around 75 cm, and it has an average height of 1.5 m. This fence was installed as an urgent measure trying to guarantee the conservation of this dry forest and reversing its regeneration collapse. In 2018, eight years after the installation of the fences, we established a 100 × 100 m plot (F1) in the more accessible zone of the exclusion area, and then we located another two (F2 and F3) in a way to avoid any plot being less than 300 m apart from each other (this is about the maximum distance that can be achieved between three 100 × 100 m plots within the fenced area: see Figure 1). We established another three plots (U1, U2, U3) outside of the fenced area, following the same 300 m rule but also avoiding that they were more than 250 m apart from the fence (see details in 15).

The excluded zone represents the area with the highest degree of conservation, characterized by restricted livestock access, which favors the natural regeneration of vegetation cover, the recovery of soil structure, and the restoration of soil biodiversity (21). In contrast, the non-excluded zone is subject to extensive grazing, mainly by goats, and has limited implementation of soil management and conservation practices, which increases the risk of degradation. In the surrounding agricultural areas, corn, rice, onions, beans, and grapes are mainly grown using conventional systems that include the use of synthetic fertilizers and pesticides, with limited adoption of sustainable strategies. According to (23), less than 40% of producers apply soil conservation practices, including fallowing and the incorporation of organic waste. According to local perception, the soils are considered fertile, although they are shallow and predominantly brown and black in color, indicating some accumulation of organic matter in the surface horizons.

## 2.2 Soil sampling and analysis

Additional to the forest zones, we also sampled in a crop zone (*Zea mays* L.), to compare the soil properties and establish differences with soil under grazing. Soil sampling was limited to 0–10 cm depth to focus on the most active soil layer where recent management impacts are most pronounced and where the majority of fine root biomass and organic matter inputs occur in tropical dry forest ecosystems (24). Also, we took 75 soil samples (total 225), for each study area, using a 10-cm-deep borehole. To determine the bulk density, a 5 cm diameter cylinder was used at a depth of 10 cm. Approximately 1 kg of soil was taken from each sample for physical-chemical analysis at 10 cm and an undisturbed sample for bulk density.

Samples obtained in the field were air-dried and passed through a 2-mm sieve. Once the samples were processed, C was analyzed using the calcination or ignition method (25). Nitrogen was determined by the Kjeldahl method modified by (26). To determine the reserves of C and N, the (27) equation was used,

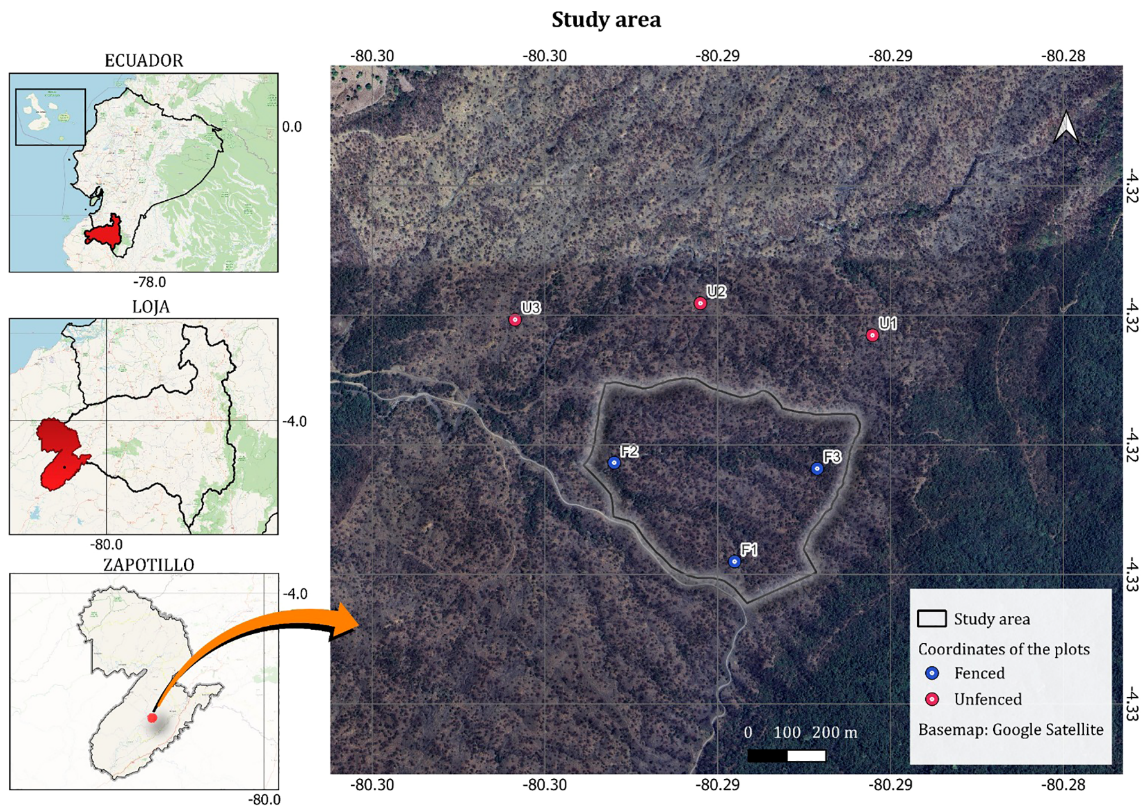


FIGURE 1
Plots location in the Zapotillo experimental field site (Valle de Palo Santo), in a dry Forest in southeastern Ecuador. Red and green points indicate unfenced (not excluded) and fenced (excluded) plots, respectively.

which considers the value of C or N, the depth, and the apparent density of each sample. Soil carbon and nitrogen stocks were calculated using the equation from (27):

$$Stock\left(\frac{Mg}{ha}\right) = C\ \ or\ \ N\ \ concentration\ \ (\%)$$
$$\times\ \ Bulk\ \ density\left(\frac{g}{cc}\right) \times\ \ Depth\ \ (cm) \times 100$$

Where:
C or N concentration = percentage of carbon or nitrogen content
Bulk density = soil bulk density at sampling depth
Depth = sampling depth (10 cm)
100 = conversion factor to express results in Mg/ha

Soil organic matter was determined using the loss-on-ignition method (25). Carbon content was estimated from organic matter using the conversion factor of 0.58 (organic carbon = organic matter × 0.58), based on the assumption that organic matter contains approximately 58% carbon (28).

The texture was also analyzed using the Bouyoucus method (29), bulk density (weight/volume) (30), pH soil: water ratio 1:2.5, The soil electrical conductivity (CE) was determined by the conductometer method, phosphorus by the method (31). Potassium, calcium, and magnesium were analyzed by Atomic Absorption (PEE/SFA/12) in the INIAP (National Institute for Agricultural Research) laboratory.

## 2.3 Statistical analysis

Statistical analyses were selected based on data distribution and research objectives. The correlation between the variables carbon stocks (C), nitrogen stocks (N), and the other elements was analyzed using the Pearson correlation coefficient, if normality was not verified, the Spearman coefficient was used. To test the effect of vegetation cover (excluded - forest, non-excluded – pasture, and crops) on C and N stocks, and soil nutrients, Generalized Mixed Linear Models (GLMM) were used with a Gaussian function for normal data and a gamma function for the distribution of error when the data were positively skewed. Generalized Linear Mixed Models (GLMM) were used to account for the hierarchical structure of the data (samples nested within plots) while handling non-normal distributions. The vegetation cover was used as a fixed factor and the plot code was used as a random factor. For this, the lme4 library (32), of the R program (R Core Team 2020) was used.

A non-metric multidimensional scaling analysis (NMDS) was also carried out, where the distances of the three land uses were determined based on the edaphic variables. Also was employed to visualize patterns in soil properties across land use types, as it is robust to non-linear relationships and does not assume normal distributions. Additionally, a principal component analysis (PCA) (33) was used to observe the grouping of the different nutrients between the study areas. For this, the "prcomp" function of the stats R library was used. Principal Component Analysis (PCA) was used to identify the land use of variation in soil nutrients and reduce dimensionality for interpretation of complex multivariate relationships.

# 3 Results

## 3.1 Physical and chemical properties of the soil

Our analysis revealed significant differences in most soil properties across the three land use types (excluded forest, non-excluded pastures, and crops). While bulk density (BD) and pH showed no significant differences across all three zones, BD did exhibit significant differences ($p<0.05$) when comparing only excluded forest with non-excluded pastures (Table 1, Supporting Information: Supplementary Figure S1). The soil pH was slightly acidic (6.41) across all zones.

Significant variations in soil texture and electrical conductivity were observed among the three study zones, with particularly notable differences between the excluded forest and non-excluded pasture areas (Table 1, Supporting Information: Supplementary Figure S1). A permutational Pearson's Chi-square test confirmed a relationship between soil texture and zone ($\chi^2$ = 32.373, p = 0.000999), with sandy-clay loam soil occurring at higher-than-expected frequencies in the cultivation zone (Figure 2).

TABLE 1 Results of General Linear Mixed Model analyses explaining variation of the edaphic parameters in three zones (EF Excluded Forest, NEP Not excluded – pastures and Cr Crops).

| Parameters | | Estimate | Std. error | *t* Value | *p* Value |
|---|---|---|---|---|---|
| **Sandy** | Cr | 56.57 | 1.93 | 29.19 | *** |
| % | EF | 10.41 | 2.30 | 4.51 | *** |
| | NEP | 17.18 | 2.30 | 7.45 | *** |
| **Clay** | Cr | 25.32 | 1.45 | 17.36 | *** |
| % | EF | -4.31 | 1.57 | -2.74 | *** |
| | NEP | -8.65 | 1.57 | -5.50 | *** |
| **Silt** | Cr | 18.10 | 1.06 | 17.01 | *** |
| % | EF | -6.10 | 1.48 | -4.09 | *** |
| | NEP | -8.53 | 1.48 | -5.72 | *** |
| **BD** | Cr | -0.142 | 0.07 | -1.90 | ns |
| g/cc | EF | -0.07 | 0.03 | -1.86 | ns |
| | NEP | 0.06 | 0.03 | 1.58 | ns |
| **pH** | Cr | 1.85 | 0.01 | 195.01 | *** |
| | EF | -0.01 | 0.01 | -0.80 | ns |
| | NEP | -0.02 | 0.01 | -1.93 | ns |
| **CE** | Cr | 4.93 | 0.07 | 62.59 | *** |
| | EF | -0.89 | 0.07 | -11.35 | *** |
| | NEP | -1.09 | 0.07 | -13.89 | *** |
| | | | | | |

Significance at 5% (***: p < 0.001, ns, not significant). BD, bulk density; CE, electrical conductivity.

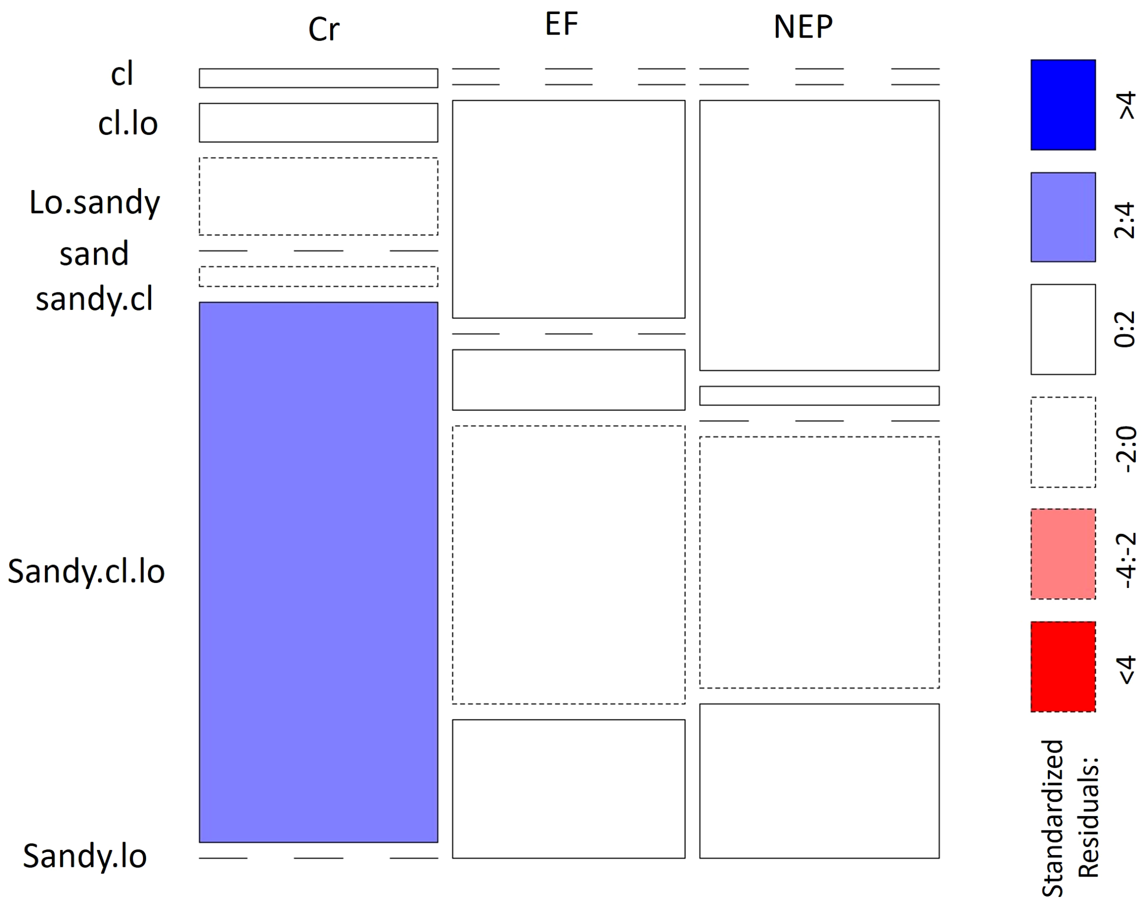


FIGURE 2
Relationship between zone (EF Excluded Forest, NEP Not excluded – pastures and Cr Crops) and soil texture. cl corresponds clay, lo refers loam.

While bulk density values remained similar across all three zones with no significant differences (Table 1), nutrient composition showed distinct patterns. Phosphorus and potassium content varied significantly across all three study zones, whereas calcium and magnesium concentrations were significantly elevated specifically in the cultivation zone (Table 2).

Correlation analysis revealed several significant relationships among soil properties. Negative correlations were observed between sand content and clay, silt, potassium, and bulk density, indicating that bulk density decreases with increasing mineral particle size. Positive correlations were found between calcium and magnesium, pH, clay, and silt, as well as between potassium and phosphorus, electrical conductivity, clay, and silt (Figure 3).

Principal component analysis identified three main components explaining soil property variations. The first component was primarily associated with carbon, phosphorus, potassium, and electrical conductivity. The second component was characterized by calcium, magnesium, and pH, while the third component was primarily associated with nitrogen, bulk density, and pH (Table 3).

The NMDS ordination achieved a final stress value of 0.087, indicating good representation of the data in two dimensions. The first axis explained 48.2% of the variation and was primarily associated with fertilization-related variables (phosphorus, potassium, electrical conductivity), while the second axis (23.7% of variation) was related to soil organic matter and texture. Clear separation among land use types was observed, with cropland sites clustering separately from forest and pasture sites primarily along the first axis. Non-metric multidimensional scaling (NMDS) further supported the distinct separation of the three land use zones based on soil properties. The cultivated sites were clearly differentiated from the other zones, primarily defined by nitrogen, pH, phosphorus, and electrical conductivity (Figure 4). The excluded forest zone exhibited lower bulk density, while the cultivated zone was characterized by elevated levels of phosphorus, electrical conductivity, and nitrogen.

The multivariate analyses collectively demonstrated that soil characteristics vary with vegetation cover. Agricultural practices such as fertilization in the cultivated zone and grazing by goats and cattle in the non-excluded zone appear to be important factors influencing the edaphic properties across the study area.

## 3.2 Soil carbon and nitrogen stocks

Soil carbon stocks were significantly higher in excluded forest (18.09 ± 2.3 Mg/ha) compared to both cropland (17.67 ± 1.8 Mg/ha;

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TABLE 2 Generalized linear mixed models for nutrients in three zones (EF Excluded forest, NEP Not excluded pastures and Cr Crops).

| Parameters | | Estimate | Std. error | *t* Value | *p* Value |
|---|---|---|---|---|---|
| **Phosphorus** | Cr | 1.77 | 0.09 | 18.14 | *** |
| mg/kg | EF | -0.73 | 0.06 | -12.08 | *** |
| | NEP | -0.80 | 0.06 | -13.11 | *** |
| **Potassium** | Cr | -0.63 | 0.11 | -5.60 | *** |
| cmol/kg | EF | -1.22 | 0.11 | -11.11 | *** |
| | NEP | -1.61 | 0.10 | -14.70 | *** |
| **Calcium** | Cr | 14.82 | 0.78 | 18.98 | *** |
| cmol/kg | EF | 1.08 | 0.80 | 1.35 | ns |
| | NEP | -0.64 | 0.80 | -0.80 | ns |
| **Magnesium** | Cr | 1.17 | 0.07 | 16.12 | *** |
| cmol/kg | EF | -0.01 | 0.10 | -0.17 | ns |
| | NEP | -0.15 | 0.10 | -1.53 | ns |

Significance at 5% (***: $p < 0.001$, ns, not significant).

p = 0.032) and non-excluded pasture (16.61 ± 2.1 Mg/ha; p = 0.018), representing increases of 2.4% and 8.9%, respectively. (Table 4, Figure 5a, Supporting Information: Supplementary Figure S1).

In contrast, nitrogen stocks showed a different pattern, with the crop zone exhibiting relatively higher average values (2.66 Mg/ha) compared to both the excluded and non-excluded zones, which averaged 2.04 Mg/ha (Table 4, Figure 5b).

# 4 Discussion

## 4.1 Physical and chemical properties of the soil

Our investigation across three distinct land use zones revealed soil textural classes ranging from sandy loam to sandy clay loam, with sand as the predominant particle fraction. In the non-excluded zone, sand content exceeded 70%, this could be related to reduced moisture retention, lower fertility, and diminished water availability, consistent with findings in similar dryland ecosystems (34, 35). The excluded zone exhibited 66% sand content, while the cultivated zone showed a notable reduction to 57%. We attribute this decrease in the cultivated zone to soil preparation practices for maize cultivation that mix superficial soil layers, while intensive erosion processes in the non-excluded pasture areas likely accelerate sand fraction loss (36). The high sand percentage throughout our study area appears to result from extensive physical weathering of rocks and minerals, limiting clay formation (37) and aligning with characteristics of the region's predominant soil orders Inceptisols, Entisols, Alfisols, and Aridisols (38) which typically exhibit coarse textures (39).

Although bulk density (BD) did not differ significantly between zones, we observed notably lower values in the excluded zone (0.81 g/cc) compared to both cultivated (0.86 g/cc) and non-excluded zones (0.93 g/cc). This pattern likely reflects greater carbon inputs from organic residues incorporated via plant biomass in the excluded zone, which increases pore space and consequently decreases BD. Conversely, in the non-excluded zone, trampling

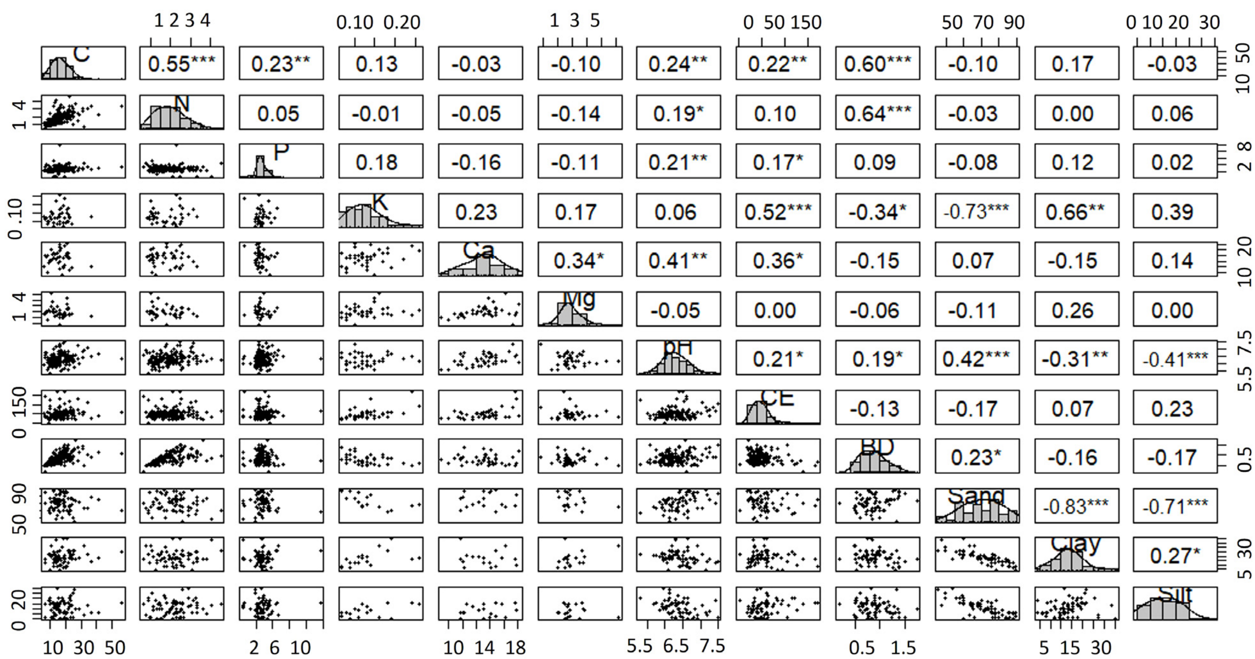


FIGURE 3
Significance matrix of soil nutrient correlations. P-values relative to Spearman's rank correlation coefficient. Values p = 0, indicate significance < 0.0001. Carbon stock (C), nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), magnesium (Mg), pH, Electrical conductivity (CE), bulk density (BD), sand (sa), clay (cl), silt (si). *** p < 0.001 (highly significant), **p < 0.01 (very significant), *p < 0.05 (significant).

TABLE 3 Loadings of the physical–chemical soil properties in each principal component. Carbon stock (C), nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), magnesium (Mg), pH, Electrical conductivity (CE), bulk density (BD).

| Parameters | CP1 | CP2 | CP3 |
|---|---|---|---|
| C | 0.256 | 0.024 | -0.277 |
| N | -0.25 | -0.027 | 0.447 |
| P | 0.425 | -0.045 | -0.054 |
| K | 0.321 | -0.176 | 0.084 |
| Ca | -0.003 | 0.494 | -0.032 |
| Mg | 0.012 | 0.404 | -0.126 |
| pH | 0.180 | 0.324 | 0.392 |
| CE | 0.398 | 0.205 | 0.048 |
| BD | -0.041 | -0.110 | 0.577 |

by goats and cattle typically creates bare soil surfaces with reduced root protection and organic matter incorporation, explaining the higher BD values observed.

Soil pH emerged as a critical driver of ecosystem multifunctionality in our study sites, consistent with findings from other dryland ecosystems (40). Despite the common occurrence of saline soils in regions with limited rainfall (37), our soil pH values across all zones (ranging from 6.27 to 6.41) were slightly acidic, providing optimal conditions for regionally important crops. This pH range facilitates nutrient availability for plants (39), representing an important edaphic factor for agricultural productivity in the region. We observed that extensive livestock grazing tended to acidify soil in dry areas, while forested areas decreased soil pH due to accumulated leaf litter. The cultivated zone exhibited higher pH values compared to other zones, likely influenced by specific agricultural management practices employed by local farmers.

Our analysis of soil nutrients revealed that phosphorus and potassium concentrations showed statistically significant differences among the study zones, with highest values recorded in the maize cultivation zone. Despite crop uptake typically reducing these nutrients, fertilizer applications partially replenish soil nutrient pools, leading to rapid increases following application (41). The application of nitrogen fertilizers can improve soil phosphorus

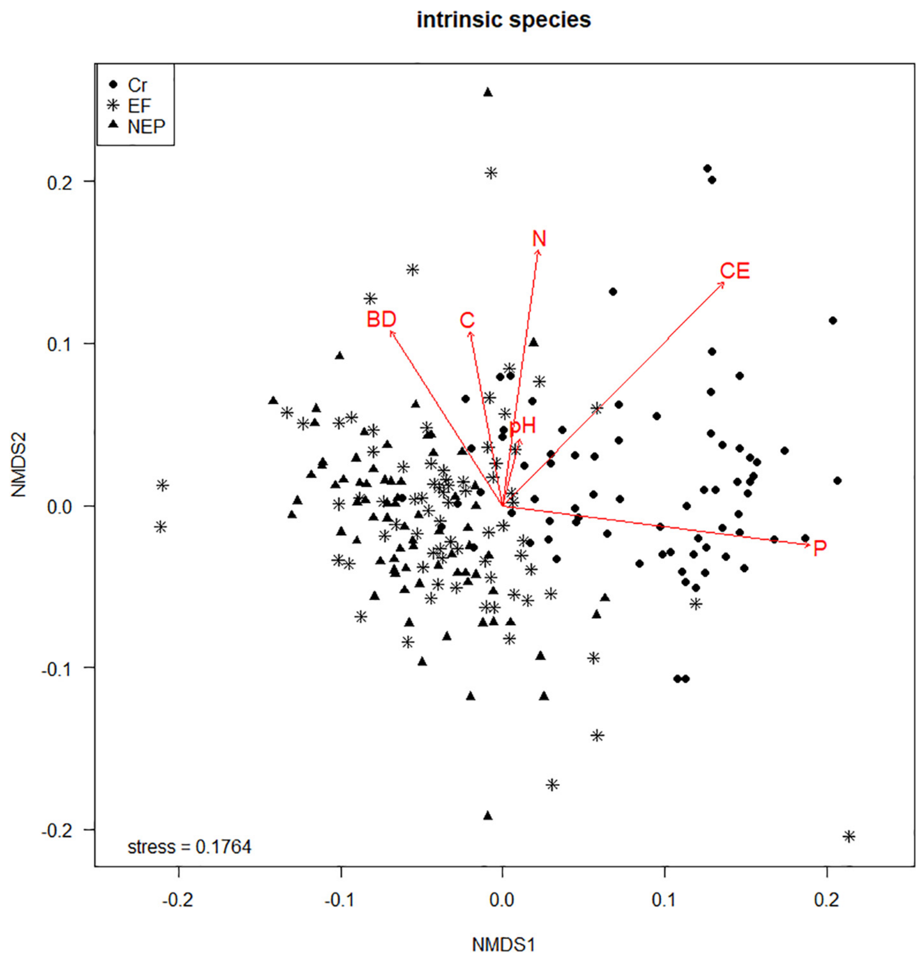


FIGURE 4
Non-metric multidimensional scaling (NMDS) using edaphic variables (bulk density, pH, carbon, nitrogen, phosphorus, electrical conductivity) in three land uses (EF Excluded forest, NEP Not excluded – pastures and Cr Crops).

TABLE 4 Model fit of the Generalized Linear Mixed Models of the soil carbon and nitrogen stocks in three study zones (Cr - crops, EF – excluded forest, NEP – non excluded pasture and crops).

| Parameters | | Estimate | Std. error | *t* Value | *p* Value |
|---|---|---|---|---|---|
| **C stock** | Cr | 2.87 | 0.05 | 55.43 | *** |
| Mg/ha | EF | 0.02 | 0.05 | 0.47 | ns |
| | NEP | -0.06 | 0.05 | -1.24 | ns |
| | | | | | |
| **N stock** | Cr | 0.97 | 0.05 | 19.50 | *** |
| Mg/ha | EF | -0.26 | 0.07 | -3.70 | *** |
| | NEP | -0.26 | 0.07 | -3.68 | *** |

C carbon, N nitrogen, P phosphorus, K potassium, Ca calcium, Mg magnesium, EC electrical conductivity, BD bulk density.
*** $p < 0.001$, statistically significant difference.
ns, not significant.

availability by activating various biological mechanisms. Nitrogen stimulates microbial growth and the production of organic acids by roots, which favors the solubilization of fixed phosphorus, especially in dry soils (8, 42). Furthermore, increased plant biomass generates more root exudates, intensifying rhizosphere activity and the release of available phosphate (43, 44). Our results indicate that these soils are predominantly sandy, so the application of nitrogen and phosphate fertilizers is essential, complemented by organic amendments, to maintain fertility and optimize crop yields (37).

## 4.2 Soil carbon and nitrogen stocks

Soil carbon stocks were highest in the excluded zone, consistent with our hypothesis and supporting evidence that forests containing diverse species more effectively sequester soil carbon (45). These areas benefit from protection provided by root systems and accumulated leaf litter, creating favorable conditions for carbon accumulation. Both grazed and cultivated zones exhibited significantly lower carbon stocks compared to the conserved zone, which we attribute to persistent grazing pressure and the extended dry seasons characteristic of these forests limiting organic matter inputs to soil. Additionally, unregulated management practices and reduced vegetation cover contribute to diminished carbon content in these areas (46). Although greenhouse gas emissions were not measured directly, our findings contribute to the broader understanding that reductions in soil carbon stocks can lead to increased emissions, as suggested by the positive relationship between soil carbon content and $CO_2$ fluxes reported in previous studies (47, 48).The relationship between land use change and carbon dynamics was further illustrated by our results, which align with (48), who demonstrated in Ghana that maize-cultivated soils stored less carbon and emitted 30-46% more $CO_2$ compared to soils in forested areas. Our data provide additional evidence of how land use changes significantly influence carbon storage, particularly when comparing natural ecosystems to agricultural systems in tropical dry forests. This information could be complemented in the future with direct measurements of greenhouse gas emissions (49).

Our results extend previous research documenting negative impacts of agriculture on carbon stocks (4, 47) and demonstrate an important relationship between crop type and carbon sequestration. We found that perennial crops such as cocoa and coffee facilitate greater carbon storage than annual crops such as maize and rice, which sequester minimal $CO_2$ due to their conventional seasonal management, as observed in our study area (50). Where agricultural activities cannot be discontinued due to socioeconomic constraints, our findings suggest that preserving soil fertility and promoting organic matter additions becomes critical to prevent carbon losses. This strategy aligns with (51), who observed that incorporating 1000 kg/ha of organic carbon into soil can

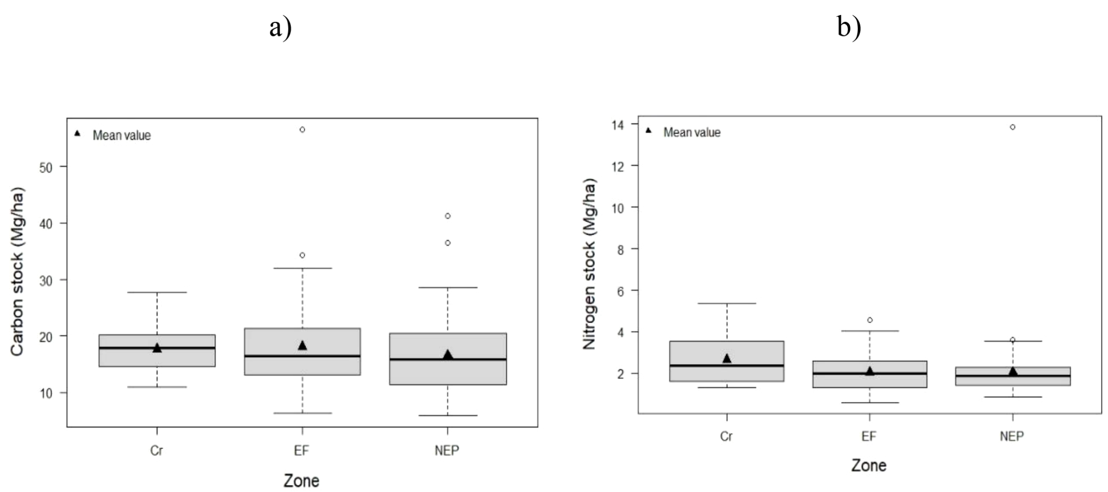


FIGURE 5
Distribution of soil C **(a)** and N **(b)** stocks in the study zones (EF Excluded forest, NEP Not excluded – pastures and Cr Crops).

increase rice yields by 10–50 t/ha and maize yields by 30–300 t/ha, demonstrating potential synergies between carbon sequestration and agricultural productivity.

Unlike the patterns observed for carbon, our results revealed that the highest soil nitrogen stocks were concentrated in the crop zone, surpassing the other areas evaluated. This finding, although unexpected, can be explained by the anthropogenic input of nitrogen derived from the frequent use of fertilizers in the agricultural systems of the study area. Farmers regularly apply nitrogen and compound fertilizers (Urea or NPK) to improve crop nutrition, which contributes to nitrogen enrichment in agricultural soils. Similar results have been reported by (52), who observed that fertilizer application significantly increased nitrogen content in semi-arid soils in China. Similarly, studies such as that of (53) also showed that omitting fertilization for four years reduced soil nitrogen accumulation to less than 60 kg/ha, highlighting the importance of agronomic management in soil nitrogen dynamics.

The sandy texture characterizing our study soils presents particular challenges for nitrogen retention. Under irrigated conditions, several studies have shown that nutrients from applied fertilizers can be easily lost through percolation and leaching (54). In this context, it has been suggested that split fertilizer application is a more efficient strategy compared to conventional practices, allowing for better synchronization between nutrient availability and crop demand, thereby reducing losses and improving nutrient use efficiency. Under irrigated conditions, several studies have shown that nutrients from applied fertilizers can be easily lost through percolation and leaching (54).

### 4.3 Management implications and sustainable development

In the semi-arid regions, we studied, resources particularly nitrogen and water are inherently limited (46, 55). This constraint characterizes our study areas, which experience extended dry seasons lasting approximately seven months annually. These lands support both livestock grazing and crop cultivation, creating significant differences in resource retention across the three land use zones we compared.

Our findings have important implications for management practices in this region, where cattle ranching and agriculture constitute the primary income sources for local residents. These activities, while economically essential, pose substantial threats to natural habitats as demonstrated by our comparative analysis of soil properties. Our results highlight the urgent need for implementing strategies that balance biodiversity conservation with agricultural productivity (56). Based on our findings, we recommend several approaches for the sustainable development of agricultural systems in dryland ecosystems: implementing more efficient fertilizer and agricultural input management, developing agroforestry systems, establishing live and dead hedgerows, transitioning to perennial crops, and incorporating organic residues (55).

Additionally, our study suggests potential for diversifying income sources through activities such as ecotourism including guided tours to appreciate *Handroanthus* sp. blooms and bicycle excursions which could promote a sustainable development model that integrates environmental conservation with community economic welfare (57). Based on the significant differences in soil properties we observed across land use zones, we emphasize that effective communication networks connecting farmers, academic institutions, and other organizations are fundamental to implementing successful soil conservation programs in similar dryland ecosystems.

## 5 Conclusion

Land use significantly influences critical soil properties including texture (proportions of sand, silt, and clay), pH, and electrical conductivity. These properties not only determine soil fertility and productivity but also regulate ecosystem functions and the capacity to support diverse vegetation communities and anthropogenic activities. Our findings indicate although the change of soil carbon stock is not significant (or only the difference between EF and Cr is significant), there is a significant difference in nitrogen stock between vegetation cover types.

We recommend promoting forest conservation initiatives and, for disturbed areas such as agricultural lands, implementing management practices that enhance soil carbon and nitrogen sequestration while maintaining fertility as strategies to mitigate global warming.

Despite the ecological significance of these relationships, data regarding carbon and nitrogen pools and soil nutrient dynamics across different land cover types remain limited. Additional research is needed to develop comprehensive models that can inform sustainable land management policies tailored to dry forest ecosystems in southern Ecuador and similar regions globally.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, Further inquiries can be directed to the corresponding author.

## Author contributions

LJ: Supervision, Funding acquisition, Conceptualization, Methodology, Writing – review & editing, Writing – original draft, Investigation, Validation. PR: Writing – original draft, Formal analysis, Methodology, Data curation, Conceptualization, Writing – review & editing. JS: Methodology, Investigation, Data curation, Writing – original draft. JB: Validation, Writing – review & editing, Methodology, Investigation. JG: Investigation, Writing – review & editing, Methodology. EG: Conceptualization, Validation, Funding acquisition, Methodology, Supervision, Investigation, Writing – review & editing, Writing – original draft.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsoil.2025.1617798/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Soil property differences between grazing-excluded and non-excluded pastures in the study area.

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